Doing Well Railway Bridge Health Management Based on Detection Technology

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Abstract: With the rapid development of China's railway sector, a large number of railway bridges are facing the demand for scientific health management. Challenges in the field of railway bridge health management include different types of natural disasters, various types of deterioration of old bridges, the adoption of a large number of new technologies for newly-built bridges, and insufficient intelligence of detection means. The technical system of railway bridge health management includes not only the organization and management means, but also the detection technology, evaluation technology, prediction and early-warning technology and maintenance decision-making technology. In terms of management, it is necessary to establish the management concept based on reliability theory, improve the standard system and establish an integrated information technology platform; in terms of technology, it is necessary to develop intelligent detection and monitoring technologies, develop risk assessment and reliability assessment theories, study bridge operation performance assessment technology, predict the residual life of bridge in detail, give scientific early warning to grave accidents, guide scientific operation and maintenance decision-making based on the concept of full life cycle cost, and develop condition-based repair and preventive maintenance.

Keywords: railway bridge; health management; detection technology; evaluation technology; prediction and early-warning technology; decision-making technology

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1 Introduction

The railway sector has been developing rapidly since the founding of the People's Republic of China. The mileages of railways in operation had reached 146 000 km by the end of the year 2020, among which the high-speed railways accounted for 38 000 km. Railway construction is inseparable from bridges, and it is necessary not only to build bridges when meeting the water, cross the existing buildings and structures such as road and pipelines, but also to build bridges instead of roads for saving land, and moreover to reduce maintenance and ensure safety. Therefore, the proportion of railway bridges in the rail line is increasing, for which there are currently a total of 19 475 bridges with the lengths of 19 749 km for the high-speed railways and a total of 70 160 bridges with the lengths of 9 931 km for the ordinary-speed railways.

Over the past several decades, constant progresses have been made with respect to the form, span, materials, design technology, construction techniques and equipment of railway bridge structure, with tens of thousands of simply-supported beam bridge, continuous beam bridge, arch bridge, beam-arch combination bridge, cable-stayed bridge and suspension bridge having been built. The representative long-span arch bridges are the Nanjing Dasheng'guan Yangtze River Bridge (steel truss arch bridge with the main span of 2×336 m) and the Beipanjiang River Bridge (reinforced concrete deck arch bridge with the main span of 445 m). In long-span cable-stayed bridges, the Tianxinzhou Yangtze River Bridge in Wuhan with the main span of 504 m and the Shanghai-Suzhou-Nantong Yangtze River Road-cum-railway Bridge with the main span of 1 092 m have been completed. In the long-span suspension bridges, the Jinshajiang River Bridge with the main span of 660 m on the Lijiang-Shangrila Railway and the Wufengshan Yangtze River Bridge with the main span of 1 092 m on the Lianyungang-Zhenjiang Railway are representative. Of course, the largest proportion of railway bridges is simply-supported beam bridge, including the forms of reinforced concrete structure, steel structure, steel-concrete structure and other forms, with spans ranging from 8 m to 132 m, among which the span of concrete simply-supported box girder erected by bridge erecting machine has reached 40 m. At present, the railway is still in the stage of rapid development. The construction of railway bridges will develop towards intelligent, green, long-span, super-deep and super-high orientation. The number will increase and the technology will progress rapidly. It is a difficult problem to be solved urgently as to how a good job should be done for the health management of a large number of railway bridges.

The report issued in 1992 by the Organization of Economic Cooperation and Development (OECD) points out that “bridge management refers to all activities which ensure the safety and functionality of a bridge, and an effective bridge management system must support the establishment of bridge management departments and their management and technical responsibilities.”[1] Therefore, bridge health management includes both technology and management organization system, which needs to be studied comprehensively from time dimension and space dimension.

2 Challenges Confronted for Railway Bridge Health Management

The rapid construction and operation of railway bridges in China have contributed to the growth of railway transport capacity. Meanwhile, it brings great challenges to maintenance and repair, and operation safety because of its large quantity, long span and complex technology. Moreover, in recent years, a large number of railway bridges have been built in areas with complex geological environment, extreme weather conditions and frequent natural disasters. Therefore, the challenges faced by bridge operation safety are multi-angle, multi-type and multiple, to which great attention must be paid.

(1) Railway bridges are widely distributed and need to face the threat of various natural disasters. Natural disasters occur frequently in China and some of which have caused great damage to bridges, such as the flood of Shiting River in Sichuan Province in 2010 which caused the collapse of Shi'ting River Bridge on the Baoji-Chengdu Railway and almost caused the serious consequences of the train falling into the river (refer to Fig. 1). At present, the bridge disaster prevention measure and early warning system are still incomplete, and it is difficult to ensure the safety of bridge in the great or extreme disaster conditions.

(2) There are many old railway bridges and many new bridges with special structures. According to statistics, more than 13 000 railway bridges have been used for over 50 years. The construction standard of these facilities is low, the investment in maintenance is large, the ability to resist natural disasters is poor, and the safety risk is high. Last year, the deterioration rate of bridges for ordinary-speed railway was 19.2%, and that of bridges for high-speed railway was 9.4%. Deterioration—repair—re-deterioration—re-repair, until scrap, repeating itself in endless cycles. If the inspection and maintenance are not timely, there will be safety risks. In recent years, new bridge structures, new forms and new equipment are constantly emerging which brings challenges to the maintenance work. If the maintenance staff cannot fully grasp the new bridge technology, they may use traditional methods to deal with failures or implement maintenance, and then cause safety accidents.

(3) Bridge intelligent detection means are not complete. At present, the detection and monitoring system of bridge equipment is not yet complete, the full life cycle safety assessment technology has not yet formed,

Fig. 1 Shiting River Bridge on Baoji-Chengdu Railway having been destroyed by floods

the problem of bridge service status depending on human inspection and experience judgment still exists and the potential safety hazards have not been completely eliminated. With the acceleration of railway construction, the operating line is getting longer and longer, and the operating speed is getting higher and higher. To ensure railway safety, especially passenger safety, it is far from enough to rely solely on traditional maintenance methods, and advanced health management methods must be implemented.

3 Studies on Railway Bridge Health Management

The railway bridge health needs to be secured by the advanced organizational management and requires the supports from the progresses of detection technology, evaluation technology, prediction and early-warning technology as well as maintenance decision-making technology. The technical systems for railway bridge health management are shown in Fig. 2.

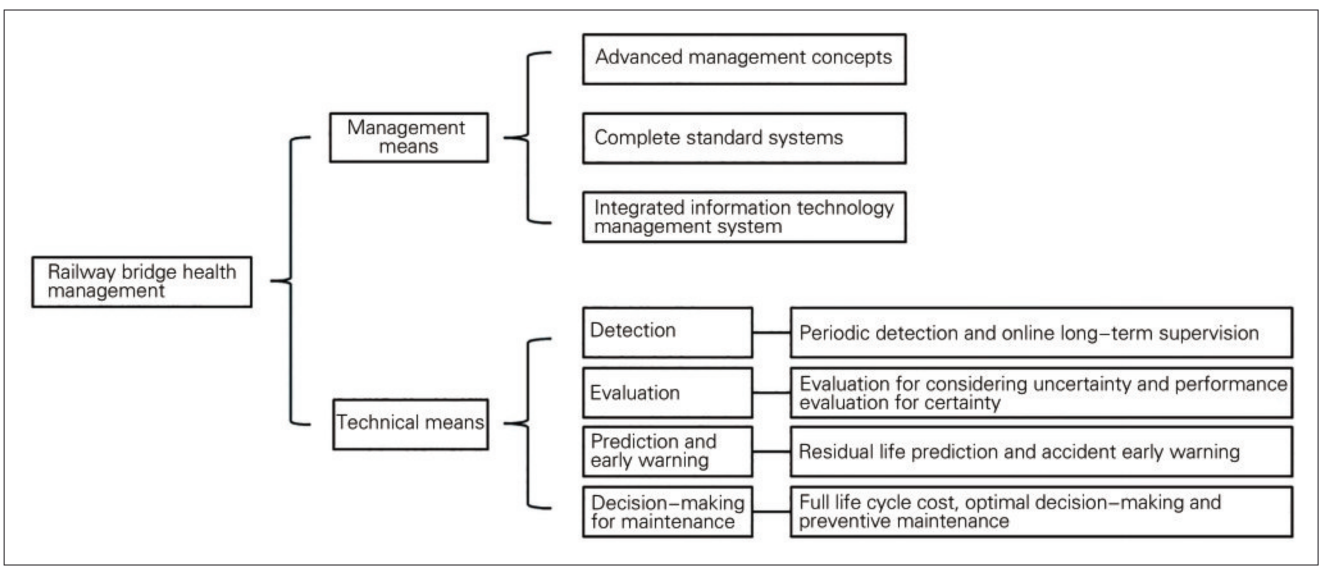

Fig. 2 Technical systems for railway bridge health management

3.1 Organizational management

3.1.1 Advanced management concepts

The railway bridge management should be guided by reliability theory, reflecting the health objectives of durability, toughness, predictability and environmental adaptability, take into account the different stages of the service process including design, construction, operation and demolition, and pay attention to the comprehensive management of personnel, equipment and environment.

For the healthy new bridges, the management concept is real-time maintenance, no lack of repair, no excessive repair so as to reduce costs; and for the bridges with a certain degree of deterioration, it is necessary to enhance the toughness of the structure including structural safety redundancy, component ductility and other performances that will help improve the reliability of the structure so as to extend the remaining life of the structures. The railway bridge health management concept is shown in Fig. 3.

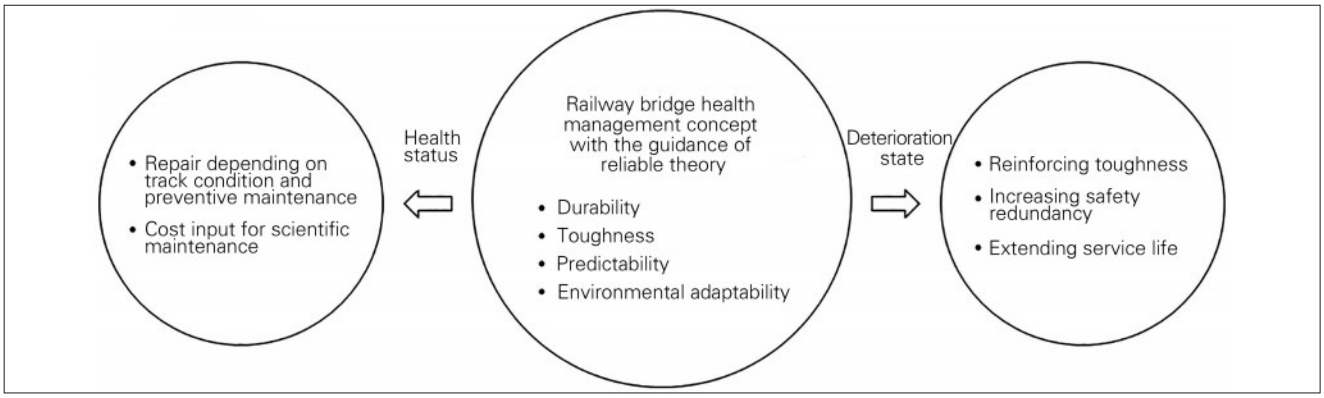

Fig. 3 Railway bridge health management concepts

3.1.2 Complete standard systems

In 1967, the Silver Bridge in the United States collapsed suddenly. People began to realize the importance of bridge detection and maintenance, and thought it necessary to formulate a unified standard, and the National Bridge Inspection Standard (NBIS) was thus promulgated in 1971. China's railways use a series of regulations such as *Railway Bridge Verification Specification* to guide the bridge maintenance. With the refined requirements of bridge health management, perfect standard systems should be formed in the aspects of deterioration assessment, detection, maintenance, service manual, and overhaul management methods.

3.1.3 Integrated Information-technology management system

The railway bridge health management needs to build the integrated information management platform, adopt BIM+GIS technology including the functional modules such as for equipment database, failure database, bridge detection, bridge monitoring, bridge evaluation, safe production management, comprehensive maintenance management, and investment decision-making, and integrate the related functions for the safe production management system of the existing railway permanent way engineering.

3.2 Detection technology

Bridge detection is classified into periodical detection and long-term online monitoring. With the maturity of satellite, robot and mobile detection technology, the integrated detection technology system of satellite-detection vehicle-ground fixed detection equipment is gradually formed, and the online monitoring of key indicators for special structure bridges is also fully promoted and applied.

(1) Satellite technology. Beidou satellite: The Beidou positioning technology is used for precise engineering survey and geodetic survey, and the horizontal precision and the vertical precision of the measuring points are controlled through adjustment post-processing so as to obtain real-time high-precision test data. Beidou test system is composed of high-precision receiver, measurement-type antenna, power adapter, feeder arrester, etc. (refer to Fig. 4).

Synthetic aperture radar interference (InSAR) satellite: small deformation such as bridge settlement can be identified by receiving radar wave phase interference image which is generated by the echo of the target and transmitting electromagnetic wave signal to the ground by space-borne radar (refer to Fig. 5).

(2) Robot technology. At pres-

Fig. 4 Bridge deformation measurement by Beidou Satellite

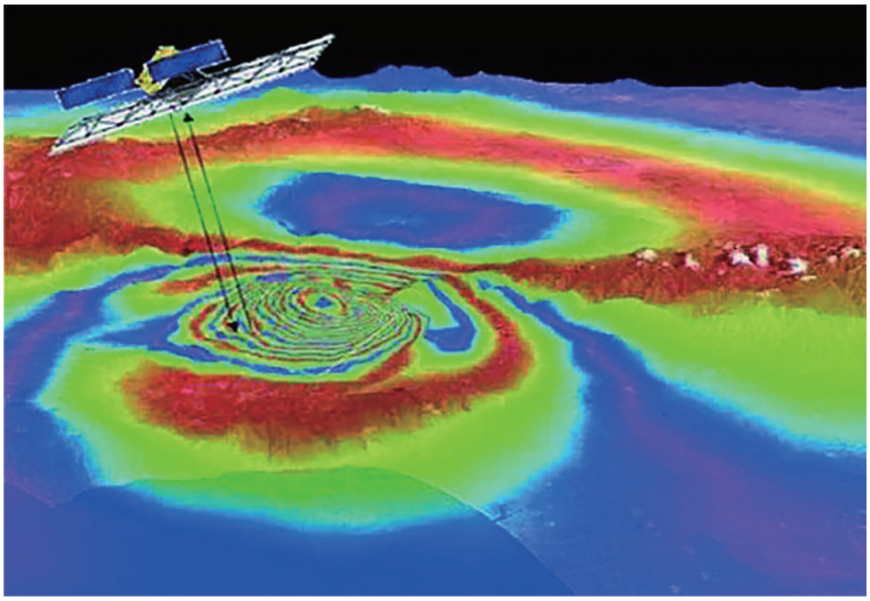

Fig. 5 InSAR satellite phase interference image

ent, there are cable-climbing robots (refer to Fig. 6), beam-bottom inspection robots (refer to Fig. 7) and underwater robots, whose detection precision is much higher than that of manual.

(3) Unmanned aerial vehicle (UAV) technology. UAVs can be used for patrol inspection.

(4) Sound-light electromagnetic non-destructive detection technology. It includes radar measurement of road surface roughness, long-term remote monitoring using electronic clinometer and ultrasonic monitoring.

(5) Moving detection technology. High-speed comprehensive detection vehicles: taking the EMU as a carrier, detecting the track geometric state of the line, the communication and signal system, the wheel-rail action force and dynamic response of the vehicle, the state and parameters of the catenary and monitoring the surrounding environment of the line according to the operating speed and at constant speed.

Comprehensive patrol inspection vehicle: Laser cameras and other equipment are installed on 120~160 km/h rail cars, and intelligent recognition technologies such as machine vision and in-depth learning are adopted to realize the appearance status inspection of key components of the three major specialties including permanent way, power supply and signaling and communication services

(6) Health monitoring technology. In addition to routine inspection, it is mainly through the health monitoring method to have a command of the state of use for the railway long-span bridge with special structure. The United States took the lead in laying sensors on many bridges in the 1980s. The test data are mainly used to verify the design assumptions, monitor the construction quality and timely assess the state of bridge structures. At the end of the 20th century, China began to carry out health monitoring of large bridges (refer to Fig. 8). The online monitoring and detection data include both dynamics data and static data. These data are integrated with climate and environmental data, and with engineering construction and maintenance data, eventually forming a comprehensive database.

3.3 Evaluation technology

Bridge health evaluations are classified into uncertainty evaluation and certainty evaluation. Uncertainty evaluation is mainly from the perspective of probability, and certainty evaluation is mainly for the service performance of bridge structures.

(1) Risk evaluation. Bridge risk evaluation is the process of identifying the potential risk related to bridge, measuring the degree of its impact and the possibility of its occurrence in some form, analyzing, comparing, evaluating and disposing the measurement results, and formulating rational countermeasures[2].

(2) Reliability evaluation. The reliability of bridge structure is the probability that the bridge structure can complete the predetermined function under the specified service conditions and within the specified service time. The health evaluation to be carried out by calculating the reliability of bridge structure has gradually become a research topic of general interest.

Fig. 6 Cable-climbing robot

Fig. 7 Bridge beam-bottom inspection robot

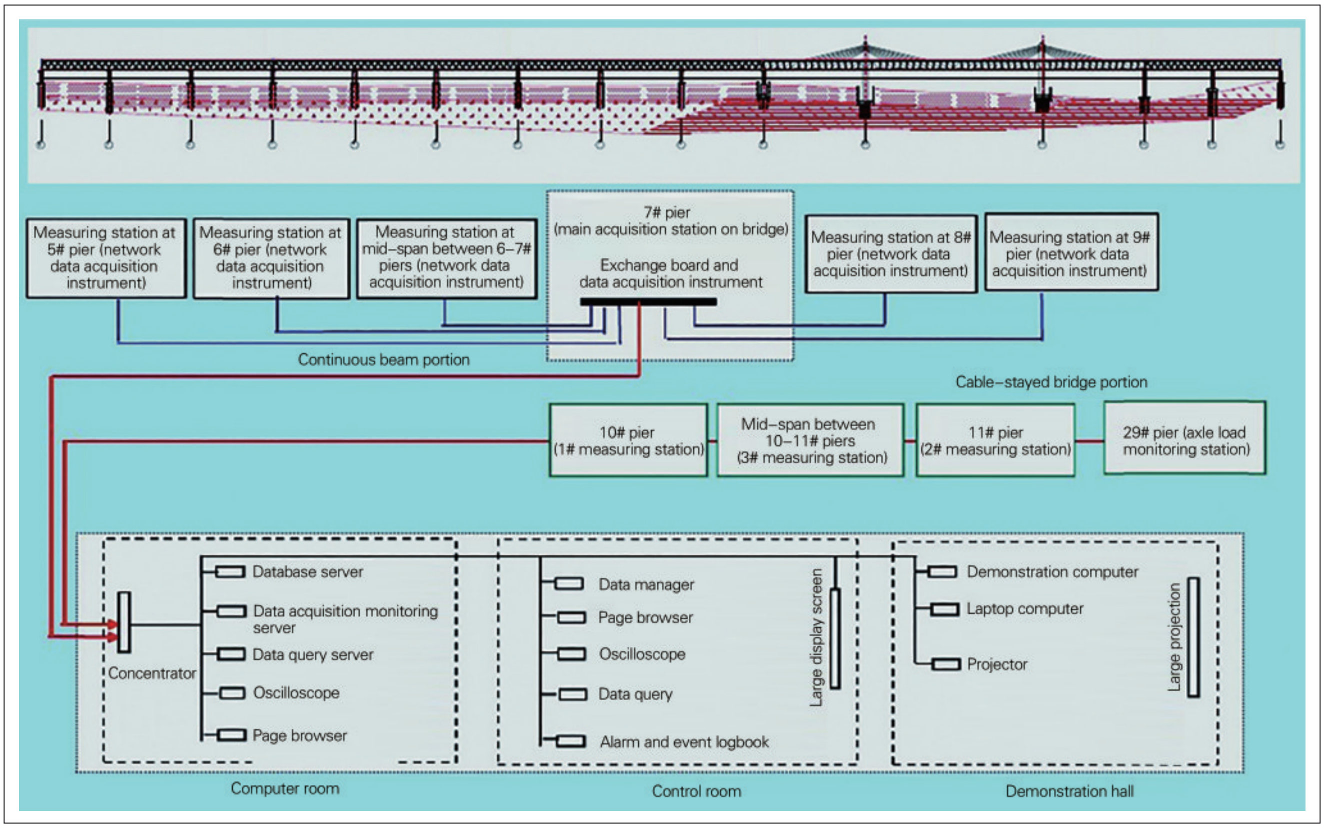

Fig. 8 Topological structure of Wuhu Yangtze River Bridge health monitoring system

China Academy of Railway Sciences Corporation Limited (CARS) has completed the reliability evaluation for the Xiangjiang River Extra-long Bridge in Xiangtan, Hunan Province for the Shanghai-Kunming Railway, for which the health monitoring system was used to get the measured data, the probability model giving consideration to the temperature effect was adopted, and train loading model was modified by using Bayesian Probability in the evaluation[3].

There are three major challenges of uncertainty in the long and major bridge evaluation including the uncertainty of measured data for bridge, complexity of structure, and weak correlation between measured data and real performance of bridge. Bayesian method is an important method to quantify the uncertainty in bridge structure evaluation based on health monitoring data. It can infer the posterior information according to the overall information, sample information and priori information[4].

According to the Bayesian theory, the posterior probability calculation of the bridge model M_i based on the measured data Y can be conducted by referring to the formula (1), and reliability of the structure can be calculated by the modified bridge model.

$$P(M_i/Y) = \frac{P(Y/M_i)P(M_i)}{\sum[P(Y/M_i)P(M_i)]} \quad (1)$$

Where: the posterior probabilities for the known measured data Y and the bridge model M_i are $P(M_i/Y)$; the priori probabilities for the unknown measured data Y and the bridge model M_i are $P(M_i)$; the conditional probabilities for the known bridge model M_i and the measured data Y are $P(M_i/Y)$; and $\sum[P(Y/M_i)P(M_i)]$ is the priori probability of the measured data which is also called the normalized constant.

(3) Performance evaluation. Verification and evaluation based on load test: bridge load test is a field test to test the static and dynamic characteristics of bridge structure or components by applying load. The test results are applied to the evaluation of bridge service condition. The test load of static load test is preferably more than 80% of the design inspection load and the loading efficiency of bridge static load test can be reduced appropriately as the axle load of the high-speed railway EMU is small. The maximum speed of dynamic load test shall not exceed 1.1 times of the allowable speed of the rail line. For the verification of the completed Shanghai—Suzhou—Nantong Yangtze River Bridge and Wufengshan Yangtze River Bridge, refer to Fig. 9 and Fig. 10 respectively.

Integrated operation performance evaluation of bridge-track-comprehensive inspection vehicle: the change of bridge service performance will eventually reflect the change of line state, and the change of line state will eventually reflect the change of train operation state. At present, the bridge structure, the track structure and the comprehensive inspection vehicle carry out their own inspection and monitoring work, and there is the phenomenon of information isolated island. CARS is taking the lead in building an integrated track-bridge detection and monitoring system.

3.4 Prediction and early warning

(1) Remaining service life prediction. Fine prediction of bridge remaining service life is significant, but it needs to be based on a large number of measured data. At present, there are methods based on recurrent neural network (RNN) and particle filter (PF)

Fig. 9 Shanghai—Suzhou—Nantong Yangtze River Bridge completion test

Fig. 10 Wufengshan Yangtze River Bridge completion test

to predict the remaining service life of the structure in the complex environment of big data, and the method using the reliability model of bridge structure to predict the remaining service life. The development of big data technology in the future is a powerful support for the accurate prediction of the remaining service life of bridge structures[5].

(2) Accident early-warning technology. The scientific early warning of major accidents of bridge structure can avoid huge losses. The earthquake early warning system developed by CARS for high-speed railway is of certain representation. The earthquake early warning system for HSR (refer to Fig. 11) that has been put into operation has realized multiple rapid train control measures for the first time; and the earthquake alarm classification disposal strategy based on the earthquake dynamic intensity has for the first time achieved P wave early warning and threshold alarm, local and remote multi-source early warning, thus forming high-speed railway earthquake early warning monitoring and automatic emergency disposal technology system with independent intellectual property rights in China and playing an important role in the safe operation of the Datong-Xi'an High-speed Railway and other lines.

3.5 Full life cycle cost and optimal decision-making

(1) Full life cycle cost (LCC). LCC is not only a scientific concept, but also a necessary prerequisite for scientific decision-making of bridge health management. Taking the simply-supported T-beam and simply-supported box beam of, passenger-freight lines as an example, the simple full life cycle estimation can see the obvious difference, because the simply-supported box beam structure has the advantages of high rigidity and good integrity, the overall deck is conducive to ensuring the waterproof effect of the waterproof system, easy to install railings, sound barriers, cable troughs and other ancillary structures. Experiences in operation and maintenance show that failures of simply-supported box beam and their workload of operation and maintenance are less than those of simply-supported T-beam (refer to Fig. 12). The comparative analysis of full life-cycle cost shows that the single-track soundless barrier box-beam bridge is 16% less than the T-beam bridge, and the double-track soundless barrier box-beam bridge is 18%~19% less than the T-beam bridge; while the single-track sound barrier box-beam bridge is 15%~16% less than the T-beam bridge, and the double-track sound barrier box-beam bridge is 16%~17% less than the T-beam bridge. Among them, in the construction cost of the whole bridge, the single-track soundless barrier box-beam bridge is 11%~16% more than the T-beam bridge, and the double-track soundless barrier box-beam bridge is 2%~9% more than the T-beam bridge; while the single-track sound barrier box-beam bridge is 5%~13% less than the T-beam bridge, and the double-track sound barrier box-beam bridge is 5%~9% less than the T-beam bridge. For the percentages of maintenance costs in the construction costs of the whole bridge are 12%~18% for box-beam bridge, 21%~26% for sound barrier T-beam, and 31%~39% for soundless barrier T-beam. Therefore, it is required that "positive efforts should be made to use the general reference drawings for box beams in the railway construction projects of passenger-freight lines" when the general reference drawings for simply-supported box beams are issued by China State Railway Group Co. Ltd.

(2) Optimal maintenance decision-making. On the basis of detection and evaluation and by depending on the intelligent decision-making support platform, timely decisions on bridge maintenance, speed restriction, scrap and other work, especially on whether to repair, when to repair and how to repair can be made, for which it is very important for railway safety and economy. Bayesian theory can be used to make decision.

(3) Condition-based repair and

Fig. 11 HSR earthquake early-warning system

Fig. 12 Deterioration phenomenon of simply-supported T-beam on mixed passenger-freight railway

preventive maintenance. At present, the railway bridges in China are mainly repaired according to the condition with the condition-based repair being combined with the planned repair. More and more attention has been paid to preventive maintenance based on durability target and big-data analysis, for which the method refers to the maintenance work required that can prevent the increase of subsequent maintenance costs due to the deterioration of the safety condition of the bridge.

4 Conclusion

Railway bridge health management needs advanced organizational management and advanced management technology and requires to establish the complete standard system, develop the intelligent periodic detection technology and online long-term monitoring technology, develop the evaluation and prediction theories with the consideration of uncertainty as well as the engineering-oriented performance evaluation and accident warning technologies so as to reflect the full life cycle cost management concept, conduct scientific decision-making, popularize the condition-based repair and carry out study on preventive maintenance. With the development of information technology, BIM technology and big data analysis technology, the railway bridge health management is facing the opportunity of upgrading and leaping for its further development.

(Translated by ZHENG Mingda)

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